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# Numerical understanding of regional scale water table behavior in the Guadalupe Valley aquifer, Baja California, Mexico

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## Abstract

A regional groundwater flow model was developed, in order to evaluate the water table behavior in the region of the Guadalupe Valley, in Baja California, Mexico. The State of Baja California has been subject to an increment of the agricultural, urban and industrials activities, implicating a growing water-demand. However, the State is characterized by its semi-arid climate with low surface water availability; resulting in an extensive use of groundwater in local aquifer. Based on historic piezometric information of the last two decades, however, a negative evolution could be observed, resulting a negative storage volume. So far, there is not an integral hydrogeological evaluation that determine the real condition of the groundwater resource, and that permit to planning a management of the Guadalupe Valley Aquifer. A steady-state calibration model was carried out in order to obtain the best possible match to measured levels at the Guadalupe Valley Aquifer. The contours of calculated water table elevations for January 1983 were reproduced. Generally, the comparison of the observed and calculated water table configurations have a good qualitative and quantitatively adjustment. Nowadays, it is count with a hydrogeological model that can be used for simulates the groundwater flow in the region of the Guadalupe Valley.

## 1 Introduction

The State of Baja California has been subject to an increment of the agricultural, urban and industrials activities, implicating a growing water-demand. However, the State is characterized by its semi-arid climate with low surface water availability; resulting in an extensive use of groundwater in local aquifer. The Guadalupe Valley is one of the most important valleys of the Northwest of Baja California, and has a high density of well heads. There are approximately 800 groundwater extraction sites (wells, dug wells and springs), but only approximately 450 of them are in use to satisfy the agricultural needs in the valley, as well as the water-demand of Ensenada City. Based on historic piezometric information reaching from 1967 to 1997 the Guadalupe Valley Aquifer has presented cyclic variations in its storage capacity, reflected by declines and recoveries of the water levels produced by the changing discharge and recharge (Beltran, 2001). During the last twenty years, however, a negative evolution could be observed, resulting a negative storage volume (Andrade, 1997). Despite the fact that the Guadalupe Valley is one of the most important valleys of Baja California, there is not an integral hydrogeological evaluation nowadays that determines the actual conditions of the groundwater resource and that permits to establish a management plan of the Guadalupe Valley Aquifer (Vazquez, 2003).

This research is the first attempt to get some insights in a rather complex hydrogeological region. This article presents the results of steady-state groundwater flow simulations in the Guadalupe Valley Aquifer.

## 2 Purpose

The purpose of this study is to test various components of a conceptual hydrogeological model, such as physical boundaries, hydraulic-parameter values, groundwater withdrawals and groundwater recharge.

A hydrogeological conceptual model is developed by taking all available data into consideration, including aquifer characteristics and groundwater-level observations. They represent the best description of the hydrogeological system as known prior to modeling based on available data and hydrological insight or understanding (Carrera et al., 1993).

## 3 Description of the study area

The Guadalupe Valley Basin is located in the Northwest part of Baja California and occupies an area of ~900 km$^2$ (Fig. 1). Which superficial drains originate in the Sierra

Juarez pass through the Ojos Negros, Guadalupe, and La Mision Valleys, reaching at the town of La Mision the Pacific Ocean. The aquifer extends over an area of ~62.75 $km^2$ (251 square cells of 0.50 km×0.50 km) measured at the downstream part of the El Porvenir Section (Fig. 2).

The regional geology information of the Guadalupe Valley Basin used in this work is the reported by the Instituto Nacional de Estadistica, Geografia e Informatica (INEGI, 1976) and borehole logs available prior to this study. In the Guadalupe Valley metamorphic rocks, intrusive and extrusive igneous rocks, conglomerates and alluvial sediments can be found (Fig. 3). The metamorphic rocks of Paleozoic age, such as slate and gneiss, are located at the Southern portion of the Calafia Section. The intrusive igneous rocks of Cretaceous age, such granodiorites, tonalities and granites, are protruding in the whole study area. The extrusive igneous rocks of Miocene age, such basalt and andesites, are protruding on the valley floor and to the West edge of the study area. The conglomerates are located at the Southern part of the El Porvenir Section and to the Eastern part of the Calafia Section. The unconsolidated alluvial sediments constitute the Guadalupe Valley Aquifer along the Guadalupe River.

In most areas, the Guadalupe Valley Aquifer is less than 2.2 km wide and has a predominantly Northeast-Southwest orientation (Beltran, 1998). The bottom boundary is formed by the contact between the aquifer and the underlaying (relatively) impermeable igneous rocks ($36\times10^{-9}$ to $365\times10^{-5}$ m/y; Domenico and Schwartz, 1998; Smith and Wheatcraft, 1993); this is treated as a no-flow boundary.

The thickness of the water-bearing units was defined by several vertical electrical-sounding logs and lithologic data from wells distributed over the region of interest. Unfortunately only little information is available about the distribution of the aquifer horizontal hydraulic conductivity. On the basis of several pumping tests in the study area, the transmissivity ranged from about $0.34\times10^{-3}$ to $52.40\times10^{-3}$ $m^2/s$, but values greater than $1\times10^{-3}$ $m^2/s$ are predominantly (Andrade, 1997).

## 4 Hydrologic system

### 4.1 Head distribution and boundaries

Groundwater levels measured in 1983 by the Comision Nacional del Agua (CNA; National Commission of Water) in the Guadalupe Valley Aquifer are assumed to represent steady-state conditions. For calibration purposes it is count with the historic water level data of a network of 39 piezometers strategically distributed throughout the modeled area. The piezometers locations are shown in Fig. 5. The groundwater levels range from 300 to 355 m above mean sea level (m a.m.s.l.).

### 4.2 Precipitation and discharge

Under predevelopment conditions, groundwater movement in much of the Guadalupe Valley Aquifer was from sources of recharge and discharged as surface and subsurface flow, as well as seepage by faults and fractures (Fig. 6) (Beltran, 2001; Andrade, 1997).

Values of the CNA precipitation data for the period 1983–2003 from the climatological stations of Agua Caliente, Olivares Mexicanos and the El Porvenir were used for the simulation (see Fig. 1). A summary of the average annual precipitation available for the three stations, within the Guadalupe Valley Region, is shown in the Fig. 7. Most precipitation falls during the winter (November–April) rainy season (Beltran, 1998).

## 5 Model construction

The Guadalupe Valley Aquifer is composed of highly permeable alluvium (18 000 to 25 000 m/y) deposited by the Guadalupe River which can yield large quantities of water to wells. Despite the fact that the aquifer is vertically heterogeneous, its regional properties suggest that it can be considered as a single system. Our approach is to treat the mixed alluvium as if it were a homogeneous deposit as similar to Wagoner and McKague (1984) and Krásný (2003). It is a simplification, since vertical facies changes are abundant in this type of depositional environment. However, it can be assumed that the vertical variation in the physical properties is probably much less severe than the lateral variation within the basin and thus our approach of averaging the properties of the entire section should be appropriate.

Bedrock outcrops occur along the Southern and Southwestern limits of the study area and are considered to be impermeable boundaries to the groundwater flow system. Interspersed among the bedrock outcrops are zones through which groundwater from the upper basin enters the system. A model in steady-state conditions with an irregular topography of the impermeable basement was assumed during the calibration (Fig. 4).

Direct infiltration of precipitation and runoff from the surrounding hills is simulated as areal recharge. The mean annual precipitation for the region was derivate from precipitation data shown in Fig. 7. Where the mean annual value is 295.15 mm/year, and is use for the estimation of the total recharge applicable to the aquifer.

## 6 Simulation of the steady-state conditions

### 6.1 Model description

A groundwater flow numeric model presented by Campos-Gaytan (2002) was used in an attempt to improve estimates for net aquifer recharge within the framework of a hydrogeological conceptual model.

The simulation consists in obtaining the computed results for the steady-state conditions. The model used in this study for describing steady-state conditions is derived by coupling Darcy's equation with the equation of continuity (Trescott, 1975; Wang and Anderson, 1982; Fetter, 2001):

$$\frac{\partial}{\partial x}\left\{K_x \cdot h(x) \cdot \frac{\partial h(x)}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{K_y \cdot h(y) \cdot \frac{\partial h(y)}{\partial y}\right\} + W = 0 \tag{1}$$



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where $K_x$ and $K_y$ are the $x$ and $y$ components of the hydraulic conductivity tensor, $\partial h(x)/\partial x$ and $\partial h(y)/\partial y$ are the gradients of head in the two coordinate directions, and $W$ is a volumetric flux per unit volume and represents sources and/or sinks of water. Equation (1) describes ground water flow under steady-state conditions in a heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the $x$ and $y$ coordinates directions. The assumptions made in using this model are that (1) flow of water is laminar, (2) the fluid is incompressible and of constant density, (3) the porous medium is rigid, (4) the coordinate axes $x$ and $y$ are aligned with the principal directions of the hydraulic conductivity tensor.

Equation (1), together with specification of flow and/or head conditions at the boundaries of an aquifer system and specification of initial head conditions, constitutes a mathematical representation of a groundwater flow system.

The numeric model used for simulate the groundwater flow solves the Eq. (1) using the central finite-differences, the fully implicit approach for the timely variation and the Successive Over Relaxation (SOR) method (Campos-Gaytan, 2002).

The aquifer domain was horizontally discretized into 828 cells, and one aquifer layer was vertically defined (see Fig. 2). Each cell has a length of 0.50 km and is of variable height, depending on the thickness of the aquifer layer it represents.

As shown in Fig. 2, the irregular boundaries become in a configuration of straight lines. The north, east, west and lower boundaries were considered as impermeable, and therefore, were incorporated in the simulator as no-flow boundaries, with exception of the sites where the mountain drains come into the valley. Several surveys of groundwater levels were carried out in the last three decades in the study area. These demonstrate that the potentiometric surface varies only slightly with time in the downstream area of the El Porvenir village. Therefore, on the basis of historic groundwater elevations cells of constant hydraulic head were assigned to the South boundary.

## 6.2 Model calibration

The calibration is a procedure by which selected model variables are adjusted within a reasonable range, in order to minimize the differences between simulated hydraulics heads and measured water levels and between simulated and measured fluxes. In this study, a steady-state calibration was carried out where model parameters were adjusted and values of recharge and discharge were estimated using trial-and-error approach. According to Boyle et al. (2000) the model parameters can be specified by borrowing values from similar watersheds that have been previously calibrated. Therefore, the information about hydraulic conductivity values have been considered from a similar watershed (Vazquez et al., 1991; Campos-Gaytan, 2002). Furthermore, values reported in the literature for the same type of analyzed materials (Anderson and Woessner, 1992; Fetter, 2001) and wells lithologic data were used to assign the hydraulic conductivities. The analysis of the information results in the hydraulic conductivity map shown in the Fig. 8, which hydraulic conductivity values of the Guadalupe Valley Aquifer ranges from 2000 to 25 000 m/year.

The model calibration was achieved through the comparison of the calculated water table and records of the water table measured in 1983 at 39 stations. In this manner, the analyzed information of the hydrogeologic conceptual model that represents the Guadalupe Valley Aquifer was integrated into the selected numeric model.

Figure 9 shows the similarity between the observed and computed groundwater-level contours, which, given the objectives of this study, was considered as a satisfactory fit.

In order to show quantitatively the accuracy of the calibration of the groundwater flow the root mean square error (RMSE) of extraction wells located in the Guadalupe Valley Aquifer was calculated according to (Anderson and Woessner 1992; Boyle et al., 2000; Reilly and Harbaugh, 2004):

$$\mathrm{RMSE} = \sqrt{\frac{1}{P}\sum_{i=1}^{P}\left[hc^i - ho^i\right]^2} \tag{2}$$

where $P$ is the number of analyzed extraction wells, $hc^i$ is the water table elevation calculated for the $i$th extraction well, and $ho^i$ is the water table elevation observed in the $i$th extraction well. The RMSE relation of the steady-state calibration results is 5.48 m for January 1983. While from a similar study reported by Freyberg (1988), the minimal RMSE is 1.26 m, the maximal RMSE is 7.96 m, and the mean RMSE is 3.56 m. Therefore, the value of 5.48 m shows an acceptable match between the calculated and measured water table elevations.

## 7 Results and discussion

The goal was to obtain a set of parameters for the groundwater flow model that would yield a best fit with the observed data (Table 1). The results of this simulation were used to check the hydrogeological conceptual model of the system. To do so, an input-output aquifer water budget was prepared. The results are shown in Table 2.

The total recharge of the Guadalupe Valley Aquifer estimated is $2.164\times10^6$ m$^3$/year, that is equivalent to 5% of the mean annual precipitation (295.15 mm/year). This recharge yield a total volume of $1.5\times10^6$ m$^3$/year (69.82% of the total recharge) by mountain-front recharge and $6.530\times10^5$ m$^3$/year (30.18% of the total recharge) by direct infiltration of precipitation (see Fig. 2). The total recharge value of the Guadalupe Valley Aquifer that provide the best fit is substancially smaller than the values calculated by Andrade (1997) and Beltran (2001).

The calculated water table elevations for steady-state conditions (wide lines in light blue color), as wells as the measured in field groundwater elevations for January 1983 (thin lines in dark blue color) are shown in the Fig. 9. The calculated hydraulic gradient has a trend similar with the measured hydraulic gradient, which has practically a Northeast-Southwest direction. Particularly, the vertical minimal differences between calculated and measured water level elevation is at the central-part of the study area (Francisco Zarco village), yield a difference of approximately 2.50 m. The vertical maximal differences are located at the Calafia Section and to the South-part of the El Porvenir Section, resulting differences in the range from approximately 5.00 m to 10.00 m. The measured groundwater elevation shows a lifting in the NW part of the study area, near to the San Miguel and the Cañada del Trigo zones, but those data could be wrong due to an incorrect vertical location of the calibration wells in that area.

Results indicate that a good coincidence exists between observed and calculated groundwater flows. However, the vertical calculated differences between the simulated hydraulic heads and the measured water levels can be attributed to limitations of the use of models, such as, the regional scale of analysis, the spatial discretization of the study area, and the quality and/or quantity of observed information that is placed in the records. The numerical model developed in this study represents an interpretation and a simplification of observed field conditions. The steady-state assumption neglects flow transience and reproduces average flow conditions. The model synthesizes the current knowledge of the hydrogeological conditions in the region. This knowledge, often qualitative, was translated into precise model parameters, a process that requires making various assumptions and simplifications. The calibration procedure allowed the estimation of the spatial distribution of the hydraulic conductivity for the permeable alluvial sediments and of the recharge rates. In addition to the non-uniqueness of the simulation results, both parameters have the potential to cause large error (Freyberg, 1988; Nastev et al., 2005). Improving the degree of understanding of both calibration parameters, and of the hydrogeologic conditions in general, would certainly improve the accuracy of the numerical model.

## 8 Conclusions

A regional groundwater flow modeling was conducted in the Guadalupe Valley Basin in the Northwest part of Baja California, Mexico. This study represents a significant advance in the understanding of the groundwater resource in the region, particularly when considering that no integral hydrogeological evaluation has been performed to date. The two-dimensional numerical model developed herein integrates the current knowledge and the hydrogeological information available for the region.

The steady-state simulation of the groundwater flow in the Guadalupe Valley Aquifer achieved satisfactory results using the hydraulic conductivity of the permeable alluvial sediments that constitute the aquifer and the areal recharge as the fitting parameters. The numerical model was calibrated against the measured potentiometric surface under the assumed steady-state conditions. The quantitative estimates of the groundwater budget show that the total flow in the region amounts to $2.164\times10^6$ $m^3$/year. The model quantitatively estimates the various components of the groundwater budget. These calculated results have formed the basis for a regional groundwater flow model of the Guadalupe Valley Aquifer. The model satisfactorily represents many aspects of the behavior of the observed potentiometric surface fixed as steady-state conditions. This study is the first step towards defining suitable groundwater management and protection strategies in the region.

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**Table 1.** Set of parameters of the Guadalupe Valley Aquifer that yield the best fit with the observed data.

| | Unity | Steady-state 1983 |
|---|---|---|
| Total Recharge | $m^3/y$ | $2.164\times10^6$ |
| Hydraulic Conductivity | m/a | 2000–25 000 |
| Cell Dimensions | m | $500\times500$ |
| Total Study Area | $km^2$ | $\sim$62.75 |
| Saturated Thickness | m | Variable |



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**Table 2.** Simulated groundwater budget for the modeled region. Values are in $m^3$/year.

| Steady-state conditions | % |
|---|---|
| Recharge | |
| Entrance flow (North boundary) (Eh)= 0.000 | 0.00 |
| Vertical recharge (RI)= $6.530\times10^5$ | 30.18 |
| Horizontal recharge (RH)= $1.511\times10^6$ | 69.82 |
| ************************** TOTAL RECHARGE = $2.164\times10^6$ ($m^3$/year) | 100.00 |
| | |
| Discharge | |
| Exit flow (South boundary***) (Sh)= $1.378\times10^6$ | 63.70 |
| Discharge by surface flow, faults and fractures (Sf)= $7.855\times10^5$ | 36.30 |
| ************************* TOTAL DISCHARGE = $2.164\times10^6$ ($m^3$/year) | 100.00 |
| | |
| Steady-state balance equation | |
| R e c h a r g e - D i s c h a r g e = 0.0 | |
| (Eh + RI + RH) - (Sh + Sf) = −7.776292 ($m^3$/year) | |
| | |
| ERROR PERCENTAGE OF THE BALANCE EQUATION = −0.000359 (%) | |
| A C C E P T A B L E | |

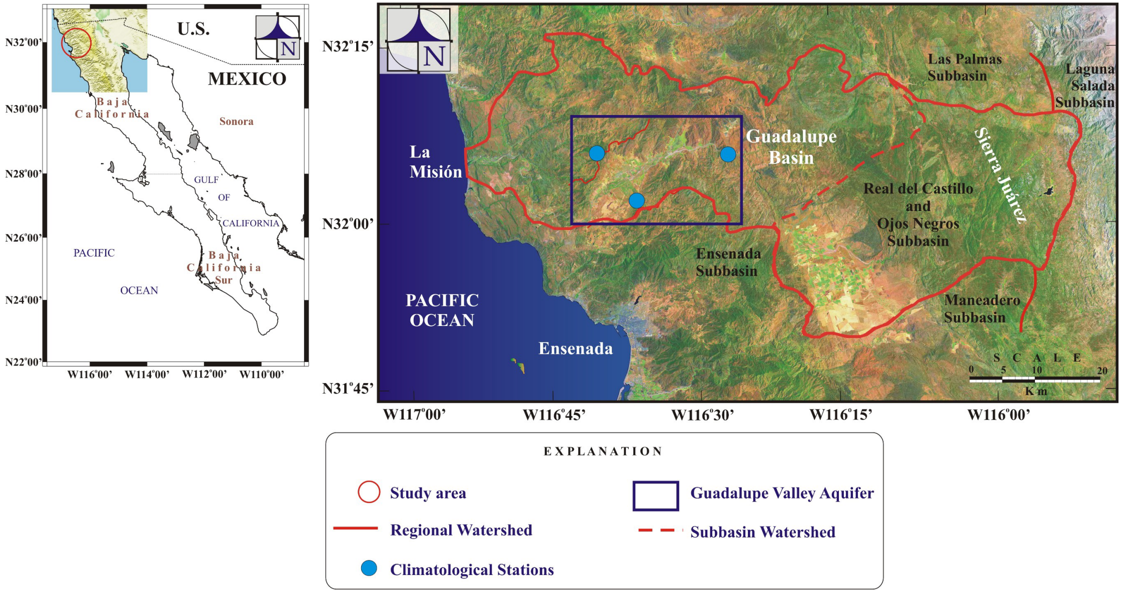


**Fig. 1.** Location of the study area.



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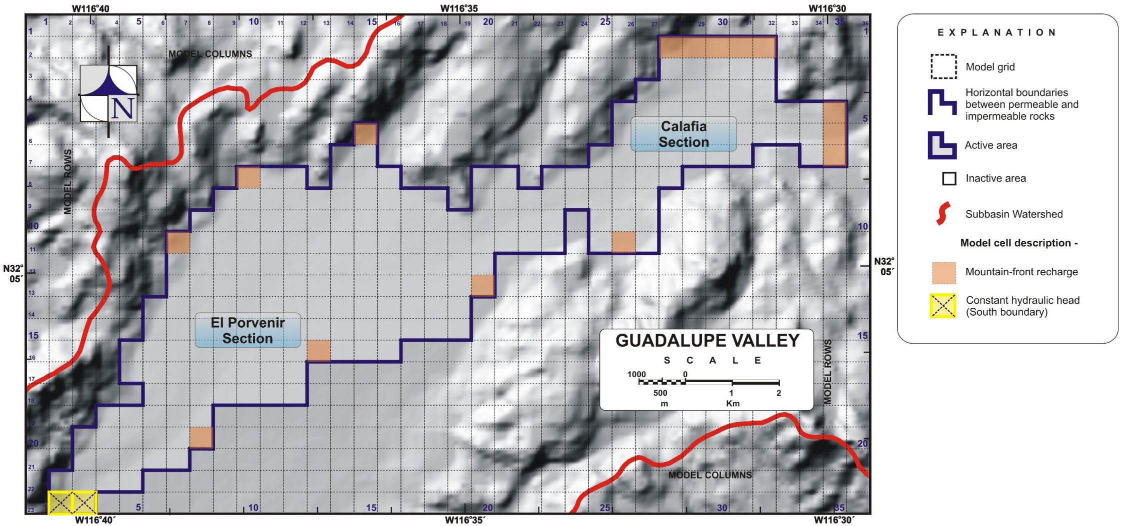


**Fig. 2.** Finite-difference grid for the groundwater flow model with location and types of boundary conditions.



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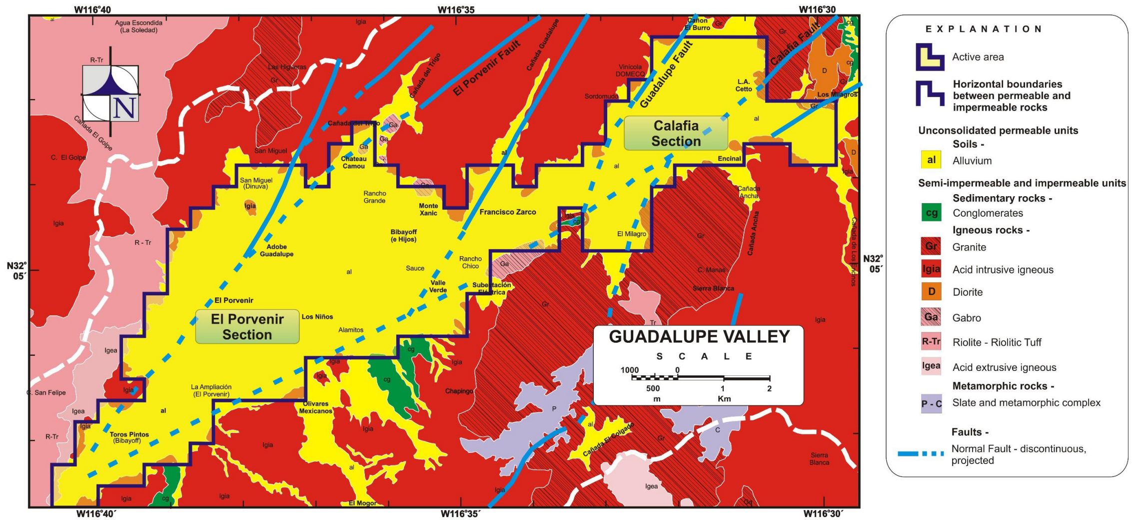


**Fig. 3.** Regional geology of the Guadalupe Valley Region (INEGI, 1976).



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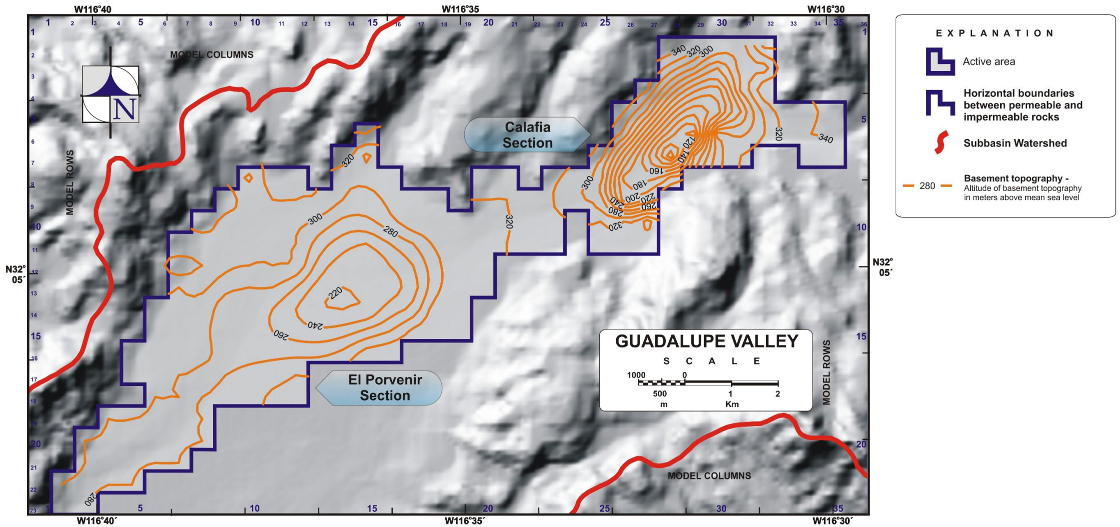


**Fig. 4.** Altitude of the base of the groundwater flow model in meter above mean sea level (m a.m.s.l.).



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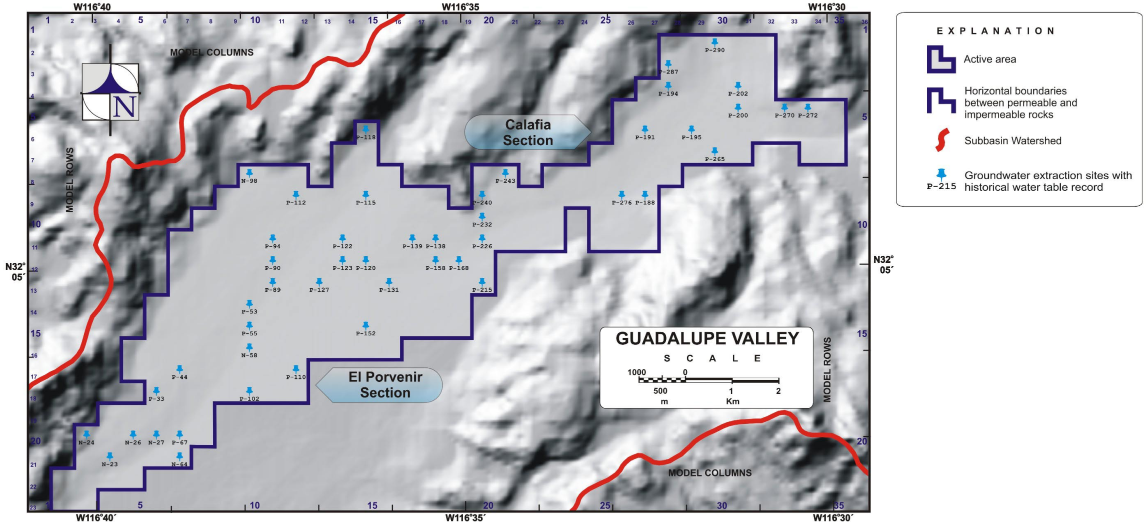


**Fig. 5.** Location of wells from which hydraulic head were taken.



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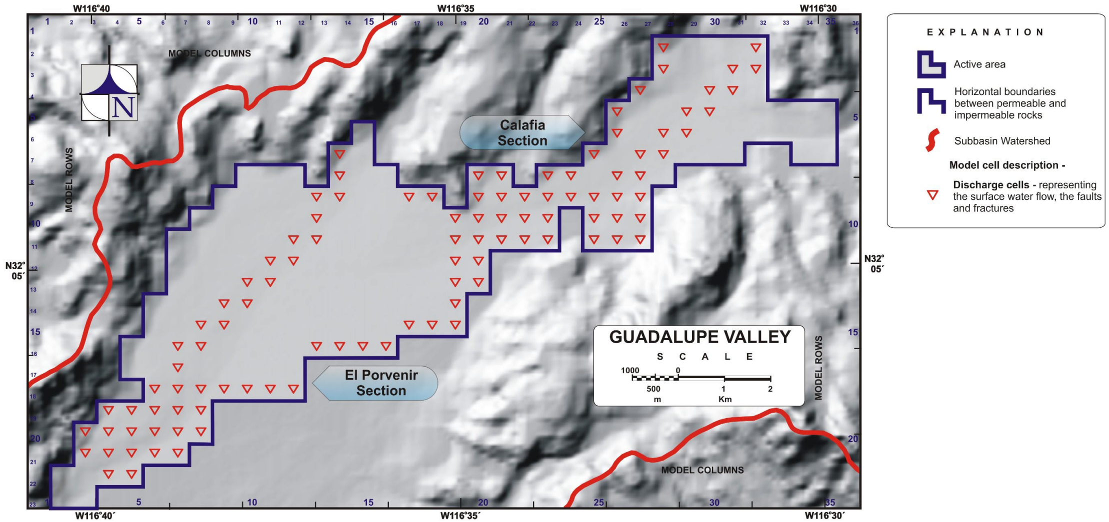


**Fig. 6.** Cell location representing discharge cell by the surface water flow, as wells as the faults and fractures used as discharge cells assigned in the groundwater flow model of the Guadalupe Valley.



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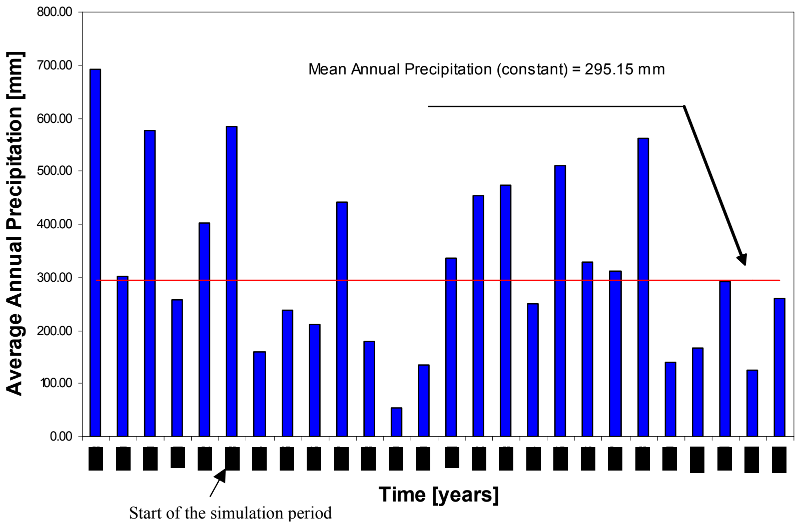


**Fig. 7.** Mean annual precipitation in the Guadalupe Valley Region based on the climatological record of the Agua Caliente, the El Porvenir and the Olivares Mexicanos stations for the period of 1978 to 2003 (Beltran, 2001).



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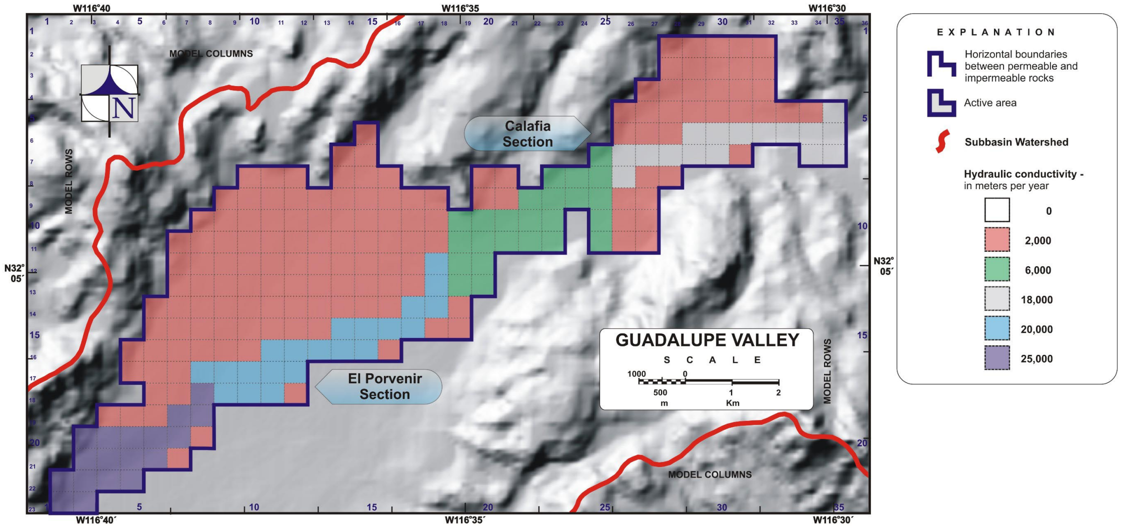


**Fig. 8.** Hydraulic conductivity zones assigned for the study are based on the geological setting.



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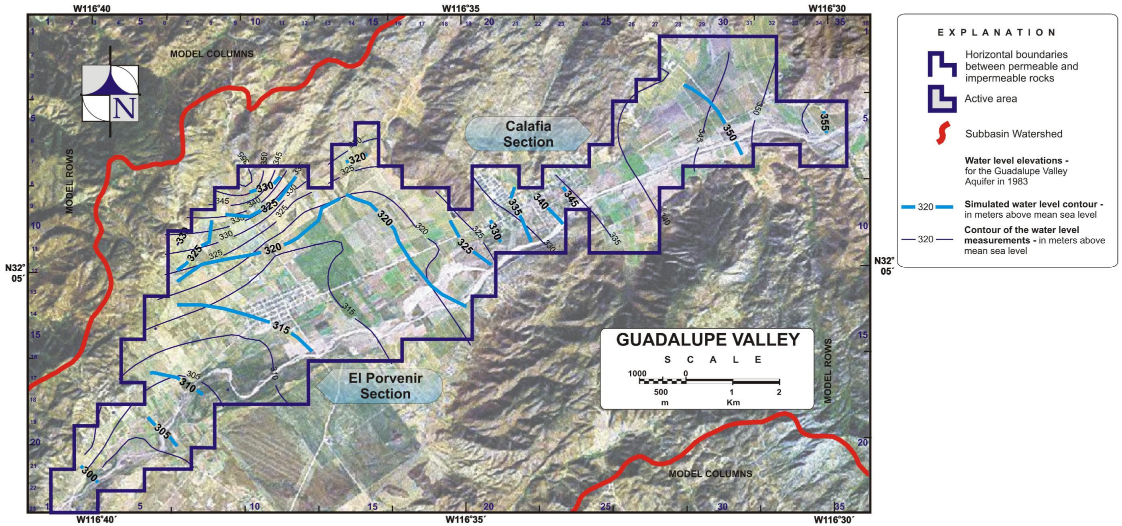


**Fig. 9.** Simulated hydraulic head that yield the best fit with the measured water table elevation for the Guadalupe Valley Aquifer in 1983.



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